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**STRUCTURE AND STABILITY OF REACTING**

**COMPRESSIBLE FREE SHEAR LAYERS**

## SUMMARY

The contract is in support of research on the structure and stability of reacting compressible mixing layers. The research performed under this contract has resulted in our learning a great deal about the structure and stability of reacting compressible mixing layers, (see the list of publications resulting from the contract).

Understanding the structure and the stability characteristics of reacting compressible free shear flows is of fundamental importance and may have possible usefulness in the development of the scramjet engine. As discussed by Drummond and Mukunda (1988), the scramjet combustor flow is complex but spatially developing and reacting compressible mixing layers of fuel and oxidizer provide the simplest relevant model. In modeling this flow it is assumed that initially the fuel and oxidizer (and any non-reactive components) are in two unmixed co-flowing streams. Mixing of the two gases takes place in the shear layer between the streams and combustion occurs when there is both sufficient fuel and oxidizer present at the same point. The residence time of the fuel and oxidizer in the combustion chamber can be very short; therefore, it is extremely important that a high mixing rate be achieved so that complete combustion is attained before the fuel is convected out of the engine. Mixing is enhanced when the basic flow is unstable. Therefore knowledge of the flow's stability characteristics may improve the understanding of the mixing process in the scramjet and is also of fundamental interest in its own right.

It has been realized for some time that the problem of a very short residence time is compounded by the experimental observations that the mixing rates of shear layers decrease as the Mach number increases from zero (e.g., Brown and Roshko, 1974; Chinzei, Masuya, Komuro, Murakami, and Kudou, 1986; Papamoschou and Roshko, 1986,

1988; and Clemens, 1992). Numerical simulations of non-reacting compressible mixing layers (e.g., Guirguis, 1988; Lele, 1989; and Sandham and Reynolds, 1990) as well as reacting compressible mixing layers (Drummond and Mukunda, 1988; Drummond, Carpenter, Riggins and Adams, 1989 for example) have also shown the same effect. Because of the increased stability, natural transition to turbulence may occur at downstream distances which are larger than practical combustor lengths resulting in incomplete combustion.

The dynamical processes governing reacting compressible flows are very complex, involving strong interaction between the chemical and fluid dynamical effects. Apart from from a full numerical simulation of the chemistry and compressible fluid dynamics, including possibly turbulence modeling or large eddy simulation, any investigation of these flows must involve considerable modeling. This, of necessity, relies heavily on the success achieved in modeling compressible non-reacting shear flows.

There is a very extensive literature dealing with stability and related topics for incompressible mixing layers (see Ho and Huerre (1984) for a comprehensive review) but, until quite recently, comparatively little dealing with even the non-reacting compressible flow. Earlier work on this problem has been reviewed by Jackson and Grosch (1989) as part of a comprehensive study of the stability of the non-reacting two dimensional compressible mixing layer. This study was extended to include the effect of variation in the thermodynamic properties on the stability characteristics (Jackson and Grosch, 1991) as well as the effect of three dimensionality of the mean flow due to skewing the fast and slow streams (Grosch and Jackson, 1991). Further results, completing the description of the discrete eigenvalue spectrum of the stability problem for the two dimensional compressible non-reacting mixing layer, were presented by Grosch, et al (1992). These studies demonstrated the inherent complexity of the stability characteristics of this flow. There is only a single band of unstable modes at subsonic Mach numbers but multiple bands at supersonic Mach numbers, including modes which are supersonic in one stream and subsonic in the other as well as those which are supersonic in both streams. These modes have phase speeds which are close to the speed of one or the other of the streams or, under certain conditions, can have phase speeds which are independent of the Mach number. An increase in the Mach number from subsonic to supersonic results in a decrease of the growth rates of the unstable modes by a factor of five to ten, as was found in experiments. Three dimensional disturbances show the same general characteristics as two dimensional disturbances. Three dimensionality of the mean flow can result in either a stabilization or destabilization of the flow depending on the magnitude of the skew in the streams and the direction of propagation of the instability waves.

Further work on the stability problem for the reacting flows modeled the combustion zone by a flame sheet (Jackson and Grosch, 1990). It was found that the addition of combustion in the form of a flame sheet had important, and complex, effects on the flow stability. In addition, it was also shown that, with sufficient heat in the flame sheet, the flow could undergo a transition from convective to absolute instability, even without the presence of a region of reversed flow in the layer.

There are of course situations in which the flame sheet model may not be a sufficiently accurate representation of the combustion process. This could be important in the calculation of the stability characteristics of the reacting flow. Therefore a return to the problem of determining the structure of the diffusion flame in a compressible, particularly supersonic, mixing layer using finite rate chemistry was undertaken (Grosch and Jackson, 1991). Numerical integration of the governing equations showed that the structure of the reacting flow can be quite complicated depending on the magnitude of the Zeldovich number. In particular, for sufficiently large Zeldovich number, the three regimes first described by Linan and Crespo (1976); ie., ignition, deflagration, and diffusion flame, occur in supersonic as well as in subsonic flows. The numerics picked up the premixed flamelets as clearly shown by the distribution of the production term. Again, depending on the magnitude of the Zeldovich number, there could be a gradual or sudden transition from an inert solution to a diffusion flame.

An analysis of both the ignition and diffusion flame regimes was presented using a combination of large Zeldovich number asymptotics and numerics. This allowed an analysis the behavior of these regimes as a function of the parameters of the problem. For the ignition regime, a well defined ignition point was shown to always exist provided the adiabatic flame temperature is greater than either freestream temperature. In all cases this ignition point is the asymptotic limit of the full numerical solutions. For the diffusion flame regime, the location of the flame changes significantly with changes in the equivalence ratio and the Schmidt numbers. It was found that are substantial changes in the temperature and mass fraction distributions as the mixing layer evolves downstream. The changes, and particularly the rate of change, in the mean profiles were shown to be very sensitive to the values of the Zeldovich and Damkohler numbers.

A major theme of much current research is mixing enhancement techniques. One obvious mixing enhancement technique is to force the shear layer at some prescribed frequency, usually computed from linear stability analysis. It is essential to determine whether reacting flows are convectively or absolutely unstable if one wishes to control the downstream evolution of the flow. An absolutely unstable flow is not sensitive to external disturbances and initial conditions; thus, experiments may not be completely reproducible nor may "flow management" techniques such as forcing be useful. Because heat release from reaction had been found to induce a transition from convective to absolute instability (Jackson and Grosch, 1990) it was deemed important to study the absolute/convective instabilities of a compressible mixing layer with finite rate chemistry using the results of Grosch and Jackson (1 91) for the mean flow.

It was found (Hu, Jackson, Lasseigne, and Grosch, 1992) that absolute instability occurs for moderate heat release without the introduction of backflow. The effects of the temperature ratio, heat release parameter, Zeldovich number, equivalence ratio, direction of propagation of the disturbances, and the Mach number on the transition value of the velocity ratio were also studied. It was found that the flame sheet model provides excellent predictions on the transition values provided one is downstream of ignition and Zeldovich numbers are greater than about 10. In particular, with fixed but small velocity ratio, it is possible to induce an absolute instability by increasing the heat release parameter or by decreasing either the equivalence ratio or the temperature ratio. If the slow stream is sufficiently cool and the heat release sufficiently large an absolute instability occurs with the fast stream moderately supersonic. For a sufficiently rich mixture the flow will always be convectively unstable. It was concluded that cooling the slow stream, using a slightly lean mixture, and having a large heat release all tended to increase the magnitude of the temperature gradient in the layer and that this causes the flow to undergo a transition from convective to absolute instability. It was also shown that effect of the direction of propagation on the transition from convective to absolute instability is a kinematic one. The flow field sees the effective Mach number in the direction of propagation.

Finally, it was found (Hu, et al, 1992) that wave packet calculations are very useful for displaying the structure of both convectively and absolutely unstable flows. Because there is both a slow and a fast branch of unstable waves an impulse generates a pair of wave packets in both the case of absolute as well as convective instability. In particular, the wave packet calculations have shown that when the reacting shear layer is absolutely unstable it is *weakly* unstable. That is, with increasing Mach number from zero and a fixed rate of heat release, the absolute instability becomes progressively weaker in that the range of negative $x/t$ over which the growth rate is non-negative grows smaller and the growth rate in this region and the speed of the upstream traveling waves also becomes smaller. Thus a wave packet will grow and spread throughout the entire domain, but it may take a long time for this to happen.

## RESULTS FROM CONTRACT

The current contract (AFOSR No. 91-0250) is in support of research on the structure and stability of reacting compressible mixing layers. This support has resulted in a number of publications. These are listed below.

"IGNITION AND STRUCTURE OF A LAMINAR DIFFUSION FLAME IN A COMPRESSIBLE MIXING LAYER WITH FINITE RATE CHEMISTRY", with T.L. Jackson. Physics of Fluids A, 3, 3087-3097, 1991.

**Abstract.** *In this paper we consider the ignition and structure of a reacting compressible mixing layer lying between two streams of reactants with different freestream speeds and temperatures using finite rate chemistry. Numerical integration of the governing equations show that the structure of the reacting flow can be quite complicated depending on the magnitude of the Zeldovich number. In particular, for sufficiently large Zeldovich number, the three regimes first described by Linan and Crespo (1976); ie., ignition, deflagration, and diffusion flame, occur in supersonic as well as in subsonic flows. An analysis of both the ignition and diffusion flame regimes is presented using a combination of large Zeldovich number asymptotics and numerics. This allows us to analyze the behavior of these regimes as a function of the parameters of the problem. For the ignition regime, a well defined ignition point will always exist provided the adiabatic flame temperature is greater than either freestream temperature. For the diffusion flame regime, the location of the flame changes significantly with changes in the equivalence ratio and the Schmidt numbers.*

"NONSEPARABLE EIGENMODES OF THE INCOMPRESSIBLE BOUNDARY LAYER", with T.L. Jackson and A.K. Kapila. in Instability, Transition and Turbulence, M.Y. Hussaini, A. Kumar, and C.L. Streett ed. Springer-Verlag, 127-136, 1992.

**Abstract.** *We report the results of a study of the response of the incompressible boundary layer to disturbances of fixed frequency which are generated within the boundary layer. We show that there exists an infinite set of eigenvalues and corresponding nonseparable eigenfunctions. Series expansions for the eigenfunctions were constructed and used to construct initial conditions for numerical computations. The results of the numerical calculations are used to examine the characteristics of these eigenmodes. Sample results are presented.*

"ABSOLUTE/CONVECTIVE INSTABILITIES AND THEIR ASSOCIATED WAVE PACKETS IN A COMPRESSIBLE REACTING MIXING LAYER", with F.Q. Hu, D.G. Lasseigne, and T.L. Jackson. Physics of Fluids A (in press), 1992.

**Abstract.** *In this paper we examine the transition from convective to absolute instability in a reacting compressible mixing layer with finite rate chemistry. The reaction is assumed to be irreversible and of the Arrhenius type. It is shown that absolute instability can exist for moderate heat release without backflow. The effects of the temperature ratio, heat release parameter, Zeldovich number, equivalence ratio, and the Mach number on the transition value of the velocity ratio are given. Our results are compared to those obtained from the flame sheet model for the temperature using the Lock similarity solution for the velocity profile. Finally we examine the structure of the wave packets produced by an*

*impulse in the absolutely unstable flow.*

"INDUCED MACH WAVE-FLAME INTERACTIONS IN LAMINAR SUPERSONIC FUEL JETS", with F.Q. Hu, D.G. Lasseigne, and T.L. Jackson. Physics of Fluids A (in press), 1992.

**Abstract.** *A model problem is proposed to investigate the steady response of a reacting, compressible laminar jet to Mach waves generated by wavy walls in a channel of finite width. The model consists of a two-dimensional jet of fuel emerging into a stream of oxidizer and are allowed to mix and react in the presence of a Mach wave flow induced by wavy walls. The governing equations are taken to be the steady parabolized Navier-Stokes equations which are solved numerically. The kinetics is assumed to be a one-step, irreversible reaction of the Arrhenius type. Two important questions on the Mach wave-flame interactions are addressed: (i) how is the flame structure altered by the presence of the Mach waves, and (ii) can the presence of the Mach waves change the efficiency of the combustion processes?*

"REACTING COMPRESSIBLE MIXING LAYERS: STRUCTURE AND STABILITY" To appear in "Recent Advances in Combustion" (Tentative Title), 60 pages, 1993.

**Abstract.** *Understanding the stability characteristics of a reacting compressible mixing layer is of fundamental importance and this flow can regarded as the simplest relevant model of the combustion process in the scramjet. The theory describing the structure and stability of this flow is reviewed. This includes the*

*structure of the mean flow and the combustion model both of which determine the stability characteristics. Among the subjects included in the review of the stability characteristics are: the eigenvalue spectrum, convective Mach number, growth rates, and the transition from convective to absolute instability. Comparisons to experimental and numerical simulation results are made where possible.*

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